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A review on the energy and exergy analysis of solar assisted heat pump systems

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Abstract

During the last decade, a number of studies have been conducted by various investigators in the design, modeling and testing of solar assisted heat pump systems (SAHPSs). This paper reviews the studies conducted on the energy and exergy analysis of SAHPS systems in Turkey and around the world as of the end of December 2004. The studies undertaken on the SAHPS systems are categorized into four groups as follows: (i) SAHPSs for water heating, (ii) SAHPSs with storage (conventional type) for space heating, (iii) SAHPSs with direct expansion for space heating, and (iv) Solar-assisted ground source heat pump greenhouse heating system (SAGSHPGHS). This paper investigates the studies on SAGSHPs, especially ground-source heat pumps, also known geothermal heat pumps, at the Turkish universities in more detail, by giving Turkey's solar energy potential.

Keywords: Ground-source heat pump; Geothermal heat pump; Solar assisted heat pumps; Heat pumps; Energy analysis; Exergy analysis; Renewable energy; Turkey

Abbreviations: BHE, borehole heat exchangers; COP, coefficient of performance; EXCEM, exergy cost energy and mass; GHPs, geothermal heat pumps; GSHPs, ground-source heat pumps; GSHPS, ground-source heat pump system; ISAHP, integral-type solar assisted heat pump; PVs, photovoltaics; SAGSHPGHS, solar assisted ground-source heat pump greenhouse heating; SAGSHPS, solar assisted ground-source heat pump system; SAHPS, solar assisted heat pump system.

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1. Introduction

Ground-source heat pumps (GSHPs), also known as geothermal heat pumps (GHPs), have been in use for years in developed countries due to their higher energy utilization efficiencies compared to the conventional heating and cooling systems. The energy performance of a GSHP system can be influenced by three primary factors: the heat pump machine, the circulating pump or well pumps, and the ground coupling or ground water characteristics [1–5]:

Air-source heat pumps have been used for many years for both space heating and cooling; however, their efficiency is influenced by the variation in outside temperature. When heat is most needed, the outside air is cooler, thus often requiring backup electric resistance heating during the coldest days. Similarly, cooling is needed during the hottest days, requiring the equipment to work at low efficiencies. GSHPs, often referred to as GHPs, overcome the problem of resource variations, as ground temperatures remain fairly constant throughout the year. Depending upon the soil type and moisture conditions, ground (and groundwater) temperatures experience little if any seasonal variations below about 10 m [2].

The GSHPs thus have several advantages over air source heat pumps. These are:

- They consume less energy to operate,
- They tap the earth or groundwater, a more stable energy source than air,
- They do not require supplemental heat during extreme low outside temperature,
- They use less refrigerant,
- They have a simpler design and consequently less maintenance, and
- They do not require the unit to be located where it is exposed to weathering.

The main disadvantage is the higher initial cost, being about 30–50% more expensive than air source units. This is due to the extra expense and effort to bury heat exchangers in the earth or providing a well for the energy source. However, once installed, the annual cost is less over the life of the system, resulting in a net savings. The savings is due to the coefficient of performance (COP), averaging over 3 for GSHP as compared to 2 for airsource heat pumps [2].

One of the first steps in the consideration of a GSHP system is a characterization of the site in terms of geology and groundwater availability. Information concerning aquifer (or aquifers) available at the site, their ability to produce water, depth to water, geology, depth to bedrock and the nature of the soil and rock (hydraulic and thermal properties) are key issues. This information guides the designer in the selection of the type of GSHP system to be used and in the design of the system (e.g. [3–5]).

Two major types exist: ground coupled (closed loop) or water source (open loop). The ground coupled uses a buried earth coil with circulating fluid in a closed loop of horizontal or vertical pipes to thermal energy to and from the earth. The water source uses a well or an open pond to provide an energy source or sink. Ground coupled systems have been used in northern Europe for many years, but were not used on commercial scale in the US until 1980. Ground coupling is used where insufficient well water is available, where the quality of the well water is a problem, where drilling and casing of wells are expensive, or where disposal of water is restricted. In the horizontal mode of ground coupled system, pipes are buried in trenches spaced a minimum of 1.5 m apart and from 1.2 to 1.8 m deep. This allows for minimum thermal interference between pipes; however, this system is affected by solar radiation [6].

The structure of the paper is as follows. The first section includes the introductory part; Section 2 describes the utilization of GSHPs worldwide and in Turkey; Section 3 give a brief utilization and historical development of solar energy in Turkey; early studies conducted on energy and exergy analysis solar assisted both heat pumps and GSHPs in the world are investigated in the fourth section; Section 5 gives a model of a greenhouse heating with solar assisted GSHPS (SAGSHPS), and the last section concludes.

2. Utilization of the geothermal heat pumps

GSHPs have had the largest growth since 1995, almost 59 or 9.7% annually in the United States and Europe. The installed capacity is 6850 MW and annual energy use is 23,214 TJ/year in 26 countries. The actual number of installed units was around 500,000 in 2000. It is also estimated that there are over a million today (e.g. [2,6–11]).

Worldwide GSHPs account for 12% of the geothermal energy used for direct applications, amounting to approximately 16,500 TJ (4580 GWh) annually. Present estimates indicate that there are over 150,000 groundwater and 250,000 ground coupled (55% vertical) heat pump installations in the USA. The annual growth rate is estimated at 10%. GSHPs account for 63% of the geothermal direct use in the USA, amounting to 12,000 TJ (3340 GWh) annually. A typical installation, which would be for single family residence, consists of a 10.5 kW (3 tons) using about 30 l/min with a 6 °C drop in the circulating fluid. This would shave about 5 kW off winter peak heating demand and about 2.5 kW from summer demand. Thus, 200,000 homes using GSHPs would avoid constructing a new 1000 MW power plant. Although the incremental cost of the ground coupled closed loop adds about US$ 3000 to the cost of a residential heating system, payback occurs in 3–5 years from money saved on utility bills. Currently, GSHP use in the USA is in the Midwestern and Southeastern states, where many utilities were offering rebates of US$ 500–2000 to home owners to install GSHP in order to take advantage of the 138 peak shaving [2,10,11].

The largest GSHP installation in the United states is the Galt House East Hotel and 140 Waterfront Office Buildings in Louisville, Kentucky [2,12]. Heating and air conditioning is

provided for 600 hotel rooms, 100 apartments, and 89,000 square meters of office space, totaling 161,650 m^2. This system can extract 177 l/s of groundwater from four wells at 14 °C and can either remove energy from the well water for heating or add heat to the well water from air conditioning. The water is then discharged in to a storm water system. The system provides 15.8 MW of cooling and 19.6 MW of heating. The hotel complex energy use is approximately 53% of a similar non-GSHP system an adjacent unit, for a monthly savings of approximately US$ 25,000 [2].

There have also been increased utilization of GSHP in Europe, especially in Germany, Austria and Switzerland. In Switzerland, more than 20,000 borehole heat exchangers (BHE) have been installed in Germany. A typical single-dwelling house has a capacity demand of about 10 kW; however, the BHE system is 30–40% higher cost in comparison with a conventional oil fired system. Environmental awareness, enforced by a governmental subsidy, is the main incentive for the BHE installations in Switzerland [2,9,10].

The concept of GSHPs, in general heat pumps, is not new. However, the utilization of GSHPs in residential buildings is new in Turkey, although they have been in use for years in developed countries and the performance of the components is well documented. The studies carried out on GSHPs in Turkey can be divided into three groups; (a) university studies, (b) case studies (GSHP industry), and (c) standardization studies (national standards).

GSHPs have been put on the Turkish market since 1998. The first installations in this year were realized as two GSHP systems with a total capacity of 26 kW, representing a total floor area of 596 m^2. These systems have had the largest growth since the beginning of the year 2000. Today, it is estimated that the installed capacity is more than 3 MW. There are no Turkish GSHPs' manufacturers yet. The majority of the installations are in the Marmara region of Turkey (in the province of Istanbul). High-income earners also prefer these systems. Design practices in Turkey normally call for U-bend depths between 11 and 13 m/kW of heating. The ground loop constitutes approximately 24–26% of the total system costs in the installations in the country. Therefore, care must be taken in the design and construction of a ground loop for a heat pump application to ensure long ground loop life and reduce the installation costs [13–21].

3. A brief utilization and historical development of solar energy in Turkey

Solar energy technologies offer a clean, renewable and domestic energy source, and are essential components of a sustainable energy future. Turkey lays in a sunny belt between 36 and 42 °N latitudes and is geographically well situated with respect to solar energy potential. The objectives of this section are to investigate many aspects of solar energy applications in Turkey and to give a brief historical development along with Turkey's solar energy potential and consumption. The following applications were taken into consideration: solar water heating, steam generation, solar cooker, solar drying, solar houses, and photovoltaics (PVs). In the early 1960s, solar energy was realized as an alternative energy in Turkey, while in the mid-1970s, solar thermal utilization technologies began gaining the high attention of universities, the government and, the industry, and have been developed at an increasing speed. Residential and industrial consumption of solar energy in Turkey started in 1986 and 1988, respectively. Solar energy use accounted for 129 kilo tons of oil equivalent (ktoe) in 2000 and is projected to be 431 and 828 ktoe in 2010 and 2020, respectively. Among all the above solar thermal utilization methods, the solar water heating has been, and will still have, the greatest emphasis in Turkey, reaching

a total annual production capacity of 1,000,000 m^2. Recently, the number of the PV installations has significantly increased and Turkey's total PV installed capacity is expected to be 3 MWp in 2010 [22].

At the beginning of the 1960s, solar energy was realized as an alternative energy in Turkey, and some curious investigators and dissertation students began to be interested in the solar energy matter. In the mid-1970s, following technological developments in the world, solar thermal utilization technologies began gaining high attention of universities, the government and the industry and have been developed in an increasing rate [23]. Since 1975, solar systems for water heating have been widely used [24]. The first passive solar system was applied in the building of Middle East Technical University in 1975 [25]. Residential and industrial consumption of solar energy in Turkey started in 1986 and 1988, respectively [26]. As for solar studies conducted by some governmental institutions and universities, Solar Energy Institute, the only solar energy institute in Turkey, was established in 1978 within the body of Ege University [27]. Until the late 1980s, solar energy and energy conservation research was carried out at the Mechanical and Energy Engineering Department of the Marmara Scientific and Industrial Research Institute and the Building Research Institute, but these were abolished due to administrative difficulties. MRI conducted studies on low temperature applications of solar energy and modeling thermal energy requirements of Turkish process industries and assessment of the potential for solar industrial process heat between 1977 and 1985. Ankara Electronics Research and Development Institute and the Turkish Scientific and Technologic Research Center (TUBITAK) were established in 1986 and are capable of designing and manufacturing systems for PV applications. The Turkish Section of the International Solar Energy Society has been operational since 1992 by permission of the Turkish government [28,29].

The solar heaters used in Turkey are thermosiphon-types (a thermosiphon system relies on warm water rising, a phenomenon known as natural convection, to circulate water through the collectors and to the tank). A solar heater is made up of two-plate solar collectors having an absorber area between 3 and 4 m^2, a storage tank with capacity between 0.15 and 0.20 m^3 and a cold storage tank, all installed on a suitable frame [30]. There are basically three types of collectors: flat-plate, evacuated-tube, and concentrating. Flat-plate collectors are the most commonly used types. In recent years, evacuated-tube collectors began to be put on the Turkish market.

Steam generation, solar cooker, solar drying, solar houses studies have been attended by Turkish researchers. Besides this, PV applications such as lighting, irrigation pumping, telecommunication systems, remote monitoring, control systems (scientific research, seismic recording, climate recording, traffic data collection, cathodic protection) are situated all around Turkey. Turkey's PV market potential is very large due to the suitability of the country for solar radiation and the large availability of the land for solar farms. Turkey's total installed PV capacity is strongly growing without an organized PV program and is estimated to reach 800 kW_p at the end of 2002. In addition, solar building technologies commercially available are not yet well known by the architects [22].

4. Studies conducted on energy and exergy analysis of solar assisted heat pump systems

During the last decade, a number of investigations have been conducted by some researchers in the design, modeling and testing of solar-assisted heat pump systems (SAHPSs). These studies undertaken on a system basis may be categorized into four

groups as follows [31–59]: (i) SAHPSs for water heating [31–37], (ii) SAHPSs with storage (conventional type) for space heating [38–49], (iii) SAHPSs with direct expansion for space heating [31,50–54], and (iv) solar-assisted ground source heat pump greenhouse heating system (SAGSHPGHS). This system can be seen as a relatively new application, which has been recently reported by the authors [56–59].

4.1. SAHPSs for water heating

Chaturvedi et al. [31] investigated a variable capacity direct expansion SAHPS, which has been used for domestic hot water application. This system employed a bare solar collector, which also acted as the system evaporator. A variable frequency drive modulated the compressor speed to maintain a proper matching between the heat pumping capacity of the compressor and the evaporative capacity of the collector under widely varying ambient conditions. Their experimental results indicated that the coefficient of performance of the system can be improved significantly by lowering the compressor speed as ambient temperature rises from winter to summer month.

The characteristic of an integral-type solar-assisted heat pump (ISAHP) was investigated by Huang and Chyng [32]. Their ISAHP experimental system consisted of a Rankine refrigeration cycle and a thermosyphon loop that were integrated together to form a package heater. Both solar and ambient air energies were absorbed at the collector/evaporator and pumped to the storage tank via a Rankine refrigeration cycle and a thermosyphon heat exchanger. The condenser released condensing heat of the refrigerant to the water side of the thermosyphon heat exchanger for producing a natural-circulation flow in the thermosyphon loop. A 105-liter ISAHP using a bare collector and a small R134a reciprocating-type compressor with rated input power 250 W was built and tested in the study. A performance model was derived and found to be able to fit the experimental data very well for the ISAHP by these investigators. The COP values for the ISAHP built in the study were in the range 2.5–3.7 depending on the water temperatures. The highest COP value in the tests was 3.83 [33].

Chyng et al. [34] studied a modeling and system simulation of an ISAHP water heater. The modeling and simulation assumed a quasi-steady process for all the components in the system except the storage tank. The simulation results for instantaneous performance agreed very well with the experiment. The simulation technique was used to analyze the daily performance of an ISAHP for 1 year. It is shown that the daily total COP was around 1.7–2.5, depending on seasons and weather conditions. The COP values were higher than 2.0 for most of the time in a year and the daily operating time varied from 4 to 8 h. The online adjustment requirement of the expansion valve was also investigated using the present simulation technique. The analysis indicated that the expansion device does not need to be controlled online. Using the 1-year simulation results, a universal daily performance correlation of the system was derived and shown experimentally.

A long-term reliability test of an ISAHP carried out by Huang and Lee [35]. The prototype has been running continuously for more than 13,000 h with a total running time larger than 20,000 h during the 5 years. The measured energy consumption was 0.019 kWh/l of hot water at 57 °C that was much less than the backup electric energy consumption of the conventional solar water heater.

Hawlader et al. [36,37] designed, fabricated, and tested a SAHP dryer and water heater. They investigated the performance of the system under the meteorological conditions of

Singapore. The system consisted of a variable-speed reciprocating compressor, collector evaporator, storage tank, air-cooled condenser, auxiliary heater, blower, dryer, dehumidifier, and air collector. The drying system was designed in such a way that some of the components could be isolated depending on the weather conditions and usage pattern. The drying medium used was air and the drying chamber was configured to carry out batch drying of food grains. A simulation program was also developed using Fortran language to evaluate the performance of the system and the influence of different variables by these researchers. The performance indices considered to evaluate the performance of the system were Solar Fraction (SF) and COP with and without a water heater. The values of COP obtained from the simulation and experiment were 7 and 5, respectively, whereas the SF values of 0.65 and 0.61 were obtained from the simulation and experiment, respectively.

4.2. SAHPSs with storage (conventional type) for space heating

Badescu [38–40] studied on model of a thermal energy storage device integrated into a SAHPS for space heating and performed first law (energy) and second law (exergy) analysis of this system. He found that both the heat pump COP and exergy efficiency decreased when increasing the thermal energy storage unit length. Also, the monthly thermal energy stored by this unit and the monthly energy necessary to drive the heat pump compressor increased by increasing this unit length. Besides this, his preliminary results indicated that the photovoltaic array could provide all the energy required by the heat pump compressor, if an appropriate electrical energy storage system would be provided.

Yamankaradeniz and Horuz [41] investigated the characteristics of a SAHP both theoretically and experimentally for clear days during the 7 months of the winter season in lstanbul, Turkey. They developed a theoretical model and a computer program was written on this basis. The characteristics such as, daily average collector efficiency and solar radiation, monthly average heat transfer at the condenser, monthly average cooling capacity, and COP were examined.

Hulin et al. [42] studied theoretically on the thermal performance of two different schemes of SAHPSs. Their calculation results indicated that the COP of a SAHPS using the second scheme was considerably higher than that of the first scheme. Yumrutas and Koska [43] designed, constructed and investigated an experimental SAHP system for space heating with a daily energy storage tank to evaluate its performance. The heating system basically consisted of a plate solar collector, a heat pump, a cylindrical storage tank, measuring units, and a heating room located in Gaziantep, Turkey (37.18°N). The effects of climatic conditions and certain operating parameters on the system performance parameters were also studied by these authors. They found that COP_{HP} was about 2.5 for a lower storage temperature at the end of a cloudy day and it was about 3.5 for a higher storage temperature at the end of a sunny day, and it fluctuated between these values in other times.

Kaygusuz [44–46] investigated the performance of a combined solar heat pump system with an energy storage in encapsulated phase change material (PCM) packing for residential heating in Trabzon, Turkey. An experimental set-up was constructed. The experimental results were obtained from November to May during the heating season for two heating systems. His experimental studies indicated that the parallel heat pump system saved more energy than the series heat pump system, because it used both air and solar as a heat source for evaporator while the series system used only solar energy stored in the storage tank.

Axaopoulos et al. [47] performed an experimental comparison of a SAHPS with a conventional thermosyphon solar system. Their experimental studies were monitored from 1993 to 1997 during summer and winter time periods. They reached the following experimental result from the operation of the SAHPS: it was impossible to use a single parameter to indicate its performance, as there were different sources of energy input, and depending on the application, either parameter would be considered more or less important.

Yumrutas et al. [48] investigated the annual performance of a SAHPS with seasonal underground energy storage and the annual water temperature distribution in the storage tank using an iterative computational procedure based on the analytical solution of the problem. It appeared that the heating system was a technically realistic alternative to fossil fuel-fired systems. The results showed that earth type and system size had considerable effects on the system performance.

Kuang et al. [49] investigated an experimental study on SAHP performance and concluded that the thermal storage tank was an important component in solar heating systems, which could modulate the mismatch between solar radiation and the heating load. In this system, the tank temperature was so close to ambient air temperature that its heat loss to the surroundings was very low. As a result, good insulation of the water tank was not critical. An auxiliary energy source was necessary for the SAHP system. It was analyzed and demonstrated that the use of an auxiliary heater inside the storage tank resulted in wastage of energy due to the large heat loss from the storage tank, and hence, the auxiliary energy consumption was higher. The use of an auxiliary heater at the load point was economically feasible.

4.3. SAHPSs with direct expansion for space heating studies

Torres-Reyes and Cervantes de Gortari [50], Torres-Reyes et al. [51] and Cervantes and Torres-Reyes [52] studied both theoretically and experimentally on a SAHP with a direct expansion of the refrigerant within the solar collector and performed a thermodynamic optimization. The maximum exergy efficiency, defined as the ratio of the outlet to the inlet exergy flow in every component of the heat pump cycle, was determined taking into account the typical parameters and performance coefficients.

Chaturvedi et al. [31,53] and Aziz et al. [54] performed the studies on thermodynamic analysis of two-component, two-phase flow in solar collectors with application to a direct-expansion SAHP. Their results showed that changes in the mass-flow rate and absorbed solar heat flux had significant effects on the collector tube length and refrigerant heat transfer coefficient. Variations of the tube inlet diameter and collector pressure had a negligible effect on the collector size, but a significant effect on the heat transfer coefficient. The increase in the vapor quality of the refrigerant mixture was gradual over the major length of the tube, with a rapid rise taking place near the end of the tube. The method used in this study can be easily extended to incorporate matching between the collector size and compressor heat-pumping capacity.

4.4. Solar assisted ground source heat pump green house heating system (SAGSHPGHS)

Although various studies were undertaken to evaluate the performance of SAHPs, to the best of authors' knowledge, no studies on the performance testing of a SAHPS with a 50 m vertical 1 1/4 in. nominal diameter U-bend ground heat exchanger for greenhouse heating

have appeared in the open literature, except those performed by the authors [55–59]. This study differed from the previous ones as follows: (i) a flat-type solar collector was directly installed into the ground-coupled loop in order to provide additional heat to the heat transfer fluid. This type of variation could reduce the required size of the ground-coupled system and increase heat pump efficiency by providing a higher temperature heat transfer fluid. Besides this, solar collectors with a storage tank and direct expansion type solar collectors that acted as an evaporator where the refrigerant was directly expanded to absorb solar energy have been used in the earlier experimental studies. (ii) The previous studies conducted on the SAGSHPS were restricted to water heating and residential heating, while this study consisted of an alternative to heating greenhouses with the utilization of a SAGSHP system.

Fig. 1 shows a schematic diagram of the experimental set-up, which is an air/refrigerant vapor compression solar-assisted heat pump composed mainly of a rated power of electric motor driving 1.4 kW compressor, 6.66 kW condenser, 8.2 kW evaporator, expansion device equipped with a series of capillary tubes with 1.5 m long and inside diameter is 1.5 mm. Beside this, the system mainly consisted of three separate circuits: (i) the ground coupling circuit with solar collector (brine circuit or water-antifreeze solution circuit), (ii) the refrigerant circuit (or a reversible vapor compression cycle) and (iii) the fan coil circuit for greenhouse heating (water circuit). The main characteristics of the elements of the SAGSHPGHS system are listed in Table 1, where the numbers in parentheses correspond to these elements as depicted in Fig. 1 [55–59]. Conversion from the heating cycle to the cooling cycle was obtained by means of a four-way valve. To avoid freezing the water under the working condition and during the winter, a 10% ethyl glycol mixture by weight was prepared. The refrigerant circuit was built on the closed loop copper tubing. The

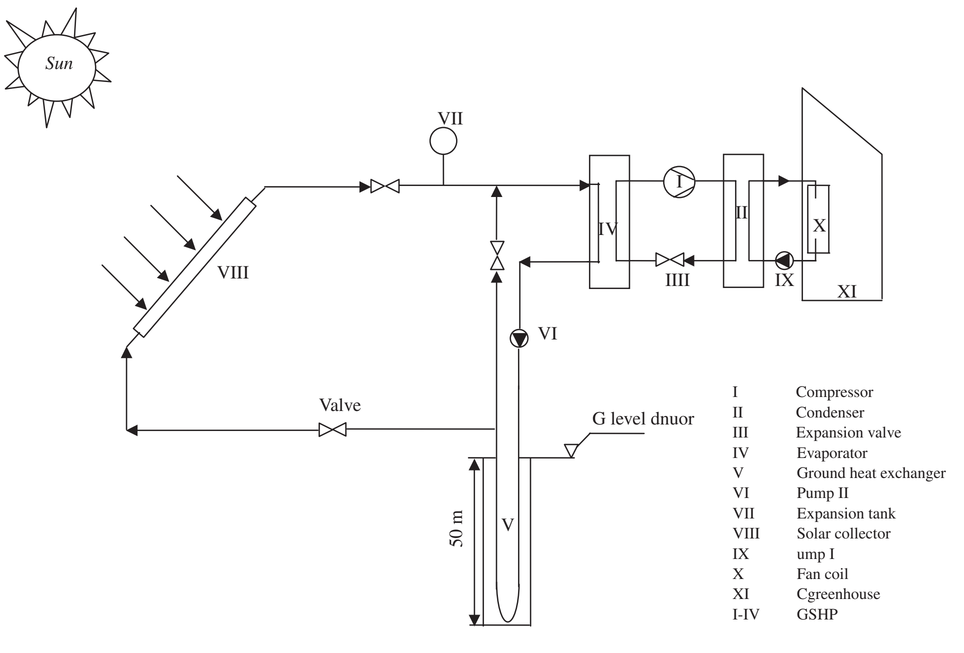

Fig. 1. The main components and schematic of the solar-assisted ground-source heat pump greenhouse heating system [55–59].

Table 1
Main characteristics of the solar-assisted ground-source heat pump greenhouse heating system [55–59]

Main circuit	Element	Technical specification
Refrigerant circuit	Compressor (I)	Type: hermetic; reciprocating; manufacturer: Tecumseh; model: TFH 4524 F; volumetric flow rate: 7.5 m^3/h; speed: 2900 rpm; the rated power of electric motor driving: 2 HP (1.4 kW); refrigerant: R-22; capacity: 4.134 kW (at evaporating/condensing temperatures of 0/45 °C);
	Heat exchanger (II) Condenser for heating Evaporator for cooling	Manufacturer: Alfa Laval; model: CB 26-24; capacity: 6.66 kW; heat transfer surface: 0.55 m^2
	Capillary tube (III)	Copper capillary tube; 1.5 m long; inside diameter: 1.5 mm
	Heat exchanger (IV) Evaporator for heating Condenser for cooling	Manufacturer: Alfa Laval; model: CB 26-34; capacity: 8.2 kW; heat transfer surface: 0.80 m^2
Ground coupling circuit	Ground heat exchanger (V)	Vertical-single U-bend type; bore diameter: 105 mm; Diameter of U-bends: 32 mm; of a bore diameter with a boring depth of 50 m; boring depth: 50 m; material: polyethylene
	Brine circulating pump (VI)	Manufacturer: Marina; type: KPM 50; range of volumetric flow rate: 0.36–2.4 m^3/h; pressure head: 41–8 m of water column, power: 0.37 kW; speed: 2800 rpm
	Expansion tank (VII)	Manufacturer: Zimmet; type: 541/L; capacity: 12 L; precharge: 1 bar
	Solar collector (VIII)	1.82 m^2, flat-type
Fan-coil circuit	Water circulating pump (IX)	Manufacturer: Marina; type: KPM 50; range of volumetric flow rate: 0.36–2.4 m^3/h; pressure head: 41–8 m of water column; power: 0.37 kW; speed: 2800 rpm
	Fan-coil unit (X)	Manufacturer: Aldag; type: SAS 28; Cooling/heating capacities: 3.25/9.3 kW, air flow rate: 600 m^3/h
	Greenhouse (XI)	GRP surface area: 48.51 m^2

working fluid was R-22. The SAGSHPGHS studied was installed at Solar Energy Institute of Ege University (latitude 38° 24′ N, longitude 27° 50′ E), Izmir, Turkey. Solar greenhouse was positioned towards the south along south-north. During the experimental period 16th of December 2003 till 31st of March 2004, *Cucumus sativus* cv. *pandora* F1 was raised, and the product quality was improved with the climatic conditions in the designed SAGSHPS. The values for COP_{HP} varied from 2.00 to 3.125, while those for COP_s were approximately 5–20% lower than COP_{HP}. The exergy efficiency values for the GSHP unit and the whole system on a product/fuel basis were obtained to be 71.8 and 67.7%, respectively. The experimental results on SAGSHPGHS also showed that the monovalent central heating operation could not meet overall heat loss of greenhouse if ambient temperature was very low. The bivalent operation could be suggested as a best solution in the Mediterranean and Aegean regions of Turkey, if a peak load heating could be easily controlled.

Table 2
Main characteristics of ground-source heat pump systems installed at the Turkish universities as of December, 2004 [55–59,64–73]

Name of university (City)	Year built	Type of GSHP system	Heat pump capacity (kW)
Middle East Technical University (Ankara) [64]	1986	A single pipe-horizontal heat pump system for the heating only with R-12; 10 m of ground coil at 1.5 m depth with a spacing of 0.6 m; COP: 1.1–1.3.	0.95
Ataturk University (Erzurum) [65,66]	1999	A water-to-water geothermal heat pump system for the heating only with R-22; an actual COP value of 2.8; geothermal water inlet/outlet temp. 35/30 °C at a mass flow rate of about 0.3 kg/s.	7.02
Ege University (Izmir)	2000	A GSHP system for both heating and cooling with a vertical-single U-bend heat exchanger; $4\frac{1}{2}$ in. of a bore diameter with a boring depth of 50 m; an actual COP value of 1.7.	5.20
Firat University (Elazig) [72,73]	2002	A GSHP system with two horizontal heat exchangers (HHEs), for both heating and cooling with R-22; average COP values of the system with 2.66 and 2.81 for HHEs at 1 m and 2 m depths respectively.	2.55
Ege University (Izmir) [55–59]	2003	A SAGSHPGHS for both heating and cooling with a vertical-single U-bend heat exchanger; $4\frac{1}{2}$ in. of a bore diameter with a boring depth of 50 m. R-22; an actual heating COP value of 3.14. The exergy actual heating COP value of 3.14. The exergy efficiency values for the GSHP unit and the whole system on a product/fuel basis are obtained to be 71.8 and 67.7%, respectively.	5.20

The authors [58] also extended their studies to perform an exergoeconomic analysis using the exergy, cost, energy and mass (the so-called: EXCEM) approach [60]. This approach involved examining data for devices in the SAGSHPGHS, and showing that correlations existed between capital costs and specific second-law-based thermodynamic losses (i.e. total and internal exergy losses). The existence of such correlations likely implies that designers, knowingly or unknowingly, incorporate into their work the recommendations of exergy analysis.

5. Studies conducted on ground-source heat pump systems at the Turkish universities

The university studies on GSHPs at the Turkish universities can be classified into two categories: theoretically and experimentally. Various theoretical studies have been reported

on GSHPs. Kilkis [61] has investigated methods of utilization of soil heat by using heat pumps. Hepbasli [62] and Ataman [63] have studied on the design of GSHPs and heating of homes. As of October, 2004, there are five experimental systems, as listed in Table 2 [55–59,64–72].

The first experimental study on GSHPs was completed by [64] in 1986 on the base of a MSc Thesis by using the available equipment in the Mechanical Engineering Department, Middle East Technical University, Ankara, Turkey. The GSHP system consisted of two circuits. One of them was the refrigeration cycle in which refrigerant 12 (R-12) was used as the refrigerant. The other one was a liquid circulation type earth coil through which water-antifreeze solution (brine) was circulating. Ground heat exchanger (earth coil) consisted of two parallel loops of 5/8″ outer diameter copper tubes with an approximate length of 10 m. The refrigeration and the brine circuits were coupled in terms of a storage tank via a coil heat exchanger.

The second experimental study was performed by Kara [65], and Kara and Yuksel [66]. The GSHP system was designed and installed for investigating geothermal resources with low temperatures in Erzurum, Turkey, which has low-temperature resources suitable for GSHP applications. This system consisted of three water loops and a refrigerant circuit.

The third GSHP system was connected to a 64 m^2 classroom of the Solar Energy Institute Building in Ege University, Izmir, Turkey [67–71]. The building constructed in 1986 uses passive solar techniques and hence it was well insulated. It has three floors and a total floor area of 3000 m^2.

The fourth GSHP system with a horizontal ground heat exchanger was connected to a test room with 16.24 m^2 floor area in Firat University, Elazig, Turkey [72]. The average COP values of the system in the different trenches, at 1 and 2 m depths, were obtained to be 2.66 and 2.81, respectively.

The last experimental system is related to a model solar greenhouse, which was integrated to the third GSHP system [55–59]. The greenhouse, made of glass reinforced plastics (GRP), has a total floor area of 10 m^2 and also uses passive solar techniques.

6. Conclusions

Heat pumps, especially GSHP systems, are recognized to be outstanding heating, cooling and water heating systems, and have been widely used for years. Most of the growth of these systems occurred in the United States and Europe. However, the interest in them is developing in other countries, such as Japan and Turkey. These systems have also been in use by combining solar energy (the so-called: SAGSHP system). It may be concluded that the effective use of SAGSHP systems with suitable technology in the modern locations will play a leading role not only Turkey but also on the world in the foreseeable future.

The energy performance of a GSHP system can be influenced by three primary factors: (i) the heat pump machine, (ii) the circulating pump or well pump, and (iii) the groundcoupling or groundwater well. In evaluating the performance of these systems, energy analysis is more commonly used one compared to exergy analysis. However, exergy can be considered as a key component for a sustainable future. Performing an exergy analysis of SAGSHP systems will aim at better identifying process efficiencies and losses. In other words, the analysis provides a designer with a better, quantitative grasp of the inefficiencies and their relative magnitudes. Furthermore, the results can draw an engineers

attention towards the components where the most availability is being destroyed and quantify the extent to which modification of one component affects, favorably or unfavorably, the performance of other components of the system. In this regard, it is expected that the review presented here will be very useful to the investigators dealing with heat pumps, especially SAGSHP systems.

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